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Development of a Semi-Automated Cost-Effective Facade Cleaning System

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1. Introduction

Nowadays the number of buildings with large glass or flat façades is increasing all over the World. These façades must be periodically cleaned with manual procedures that supposed high cost and risk for the workers that have to develop their work under heavy conditions. Although the cleaning cost depends a lot on several factors as the façade characteristics, the cleaning periodicity or the total surface to be cleaned, the average cost is € 8-9 per square meter. A typical building of 12.000 m² supposes a total façade cleaning cost of € 100.000 and this task is usually done every year. The use of an automatic or semi-automatic cleaning system can lead to around 60% savings over existing practice (Gambao & Hernando, 2006). Automation and robotics technologies allow environmentally friendly façade cleaning, helping to reduce the cost of these tasks. Additionally, these systems overcome the current worker safety problems associated with difficult and dangerous access, contributing to a zero injury and fatality working practices (Elkman et al., 2002).

Because of the increasing number of high-rise buildings and large glass façades and the resulting problem of safe and effective cleaning, a lot of effort has taken place in the last few years to develop automated cleaning systems. The majority of systems conceived and developed thus far are in Japan and Europe (Schraft et al., 2000) (Gambao & Balaguer, 2002). The first automated cleaning systems for high-rise building were used in Japan in the middle of the 80's. These systems were mainly designed for use on specific buildings. For safety purposes or in order to guide the robot's movement on the façade, they often required additional construction such as guidance rails to the façade.

The practical application of the existing systems mostly failed because of either a weak safety concept, poor cleaning quality, required additional construction to the façade, or simply due to expensive initial or operating costs. At this time, there is only one known system that is in continuous practical operation. That is the automatic system for the cleaning of the vaulted glass hall of the Leipzig Trade Fair, Germany (Figure 1), which was developed by the Fraunhofer Institute IFF, Germany (Elkman et al., 1999). It must also be added that this system is only applicable to this particular building.

Many of previous developed robotic façade cleaning has been designed to operate in a complete automatic way (one example is in figure 2). Although some of these systems have

successfully solve the numerous technical problems related to façade climbing operations, in most of the cases they can not be practically used due to the extremely expensive operating cost of such a complex machines. Many remain as prototypes that are very good demonstrators of high technology but can not be introduced in the market.



Fig. 1. Automatic Facade Cleaning System for the Vaulted Glass Hall of the Leipzig Trade Fair (Fraunhofer FhG)



Fig. 2. SIRIUSC – Automatic Facade Cleaning System (Fraunhofer FhG, Dornier Technologie)

Table 1 shows the different known robotic façade cleaning systems.

Manufacturer	Robot	Country	Application	Kinematics	Overcoming of obstacles	Facade type
Taisei	Exterior Wall Painting Robot	Japan	Coating	rail guided	No	Vertical
Taisei	Tile Separation Detection Robot	Japan	Tile inspection	Tensed up with cables from roof to floor	No	Vertical
Kumagai Gumi Co. Ltd.	KFR-2	Japan	Coating	Cables, vacuum cups	No	Vertical
Shimizu Corporation	SB- Multi Coater	Japan	Coating	rail guided	No	Vertical
Kajima Corporation	Tile Separation Detection Robot	Japan	Tile inspection	Tensed up with cables from roof to floor	No	Vertical
Kumagai Gumi Co. Ltd.	Automatic Diagnosis System of Tiled Wall Surfaces	Japan	Tile inspection	Tensed up with cables from roof to floor, wheels	Yes	Vertical
Toshiba Cooperation	Vacuum Suction Self-Traveling Wall Washing Machine	Japan	Wall cleaning	Vacuum cups	No	Vertical
Obayashi Corporation	Wall Inspection Robot	Japan	Inspection	Vacuum cups, secured by cables	Yes	Vertical
Takenaka Komuten Co. Ltd.	SC 11-101	Japan	Tile inspection	Vacuum cups, secured by cables	No	Vertical
Tokyo Construction Co. Ltd.	Wall-Surface Operation Robot	Japan	Tile inspection	Vacuum cups, secured by cables	No	Vertical
Mitsubishi Electric Cooperation	Automatic Window Cleaning System	Japan	Façade cleaning	Rail guided	No	Vertical
Shimizu Corporation	Canadian Crab	Japan	Façade cleaning	Vacuum cups, secured by cables	Yes	Inclined
Fraunhofer-Institut IFF	Cleaning robot for the Glasshall Leipzig Trade fair	Germany	Façade cleaning	wheels, secured by cables	No	Convex
Comatec	-	France	Façade cleaning	Vacuum cups	No	Inclined
Robosoft	-	France	Façade cleaning	Rail guided	No	Horizontal
Robosoft	Autonomous Window Cleaner Robot for High Buildings (EC: AUTOWIND)	France	Façade cleaning	Rail guided	No	Vertical
Fraunhofer-Institut IFF, Dornier Technologie	SIRIUSc	Germany	Façade cleaning	Rail guided	Yes	Vertical
Newcastle University; OCS Group; Cradle Runways	Arcow	UK	Façade cleaning	Rail guided	No	Vertical
CSIC	Tito	Spain	Façade cleaning	Air suction	No	Vertical

Table 1. Façade cleaning robots

In the frame of an European founded project, a consortium formed by several enterprises and research centres has develop a low cost semi-automated system for the cleaning of building façades, addressing an innovative concept of system that is able to work in different types of homogeneous building façades, increasing the productivity, reducing the risk for workers nearly to zero and contributing to preserve the environment. This system is with minor changes adaptable to the largest possible number of buildings with homogeneously-designed façades. Additional constructions to the façade such as guide rails or scaffoldings are avoided or made unnecessary. The requirements for the control and sensor concepts are very specific, because the proposed robotic system is able to operate under adverse conditions such as changing weather conditions.

In this chapter, we present the description of the robotic façade cleaning system (denominated *CAFE*) and, after that, the selected control architecture and the implementation of this concept in the real system.

2. Concept of the *CAFE* robotic cleaning system

All the high buildings use commercial carrier systems that support a gondola that moves on the façade for manual cleaning. One or two operators are needed for this task. Based in the existence of the carrier system on the building roof, the *CAFE* robotic system uses it to reduce the costs of the vertical and horizontal movements. The system uses a commercial carrier with minor modifications for movements in axes X and Y (Figure 3).

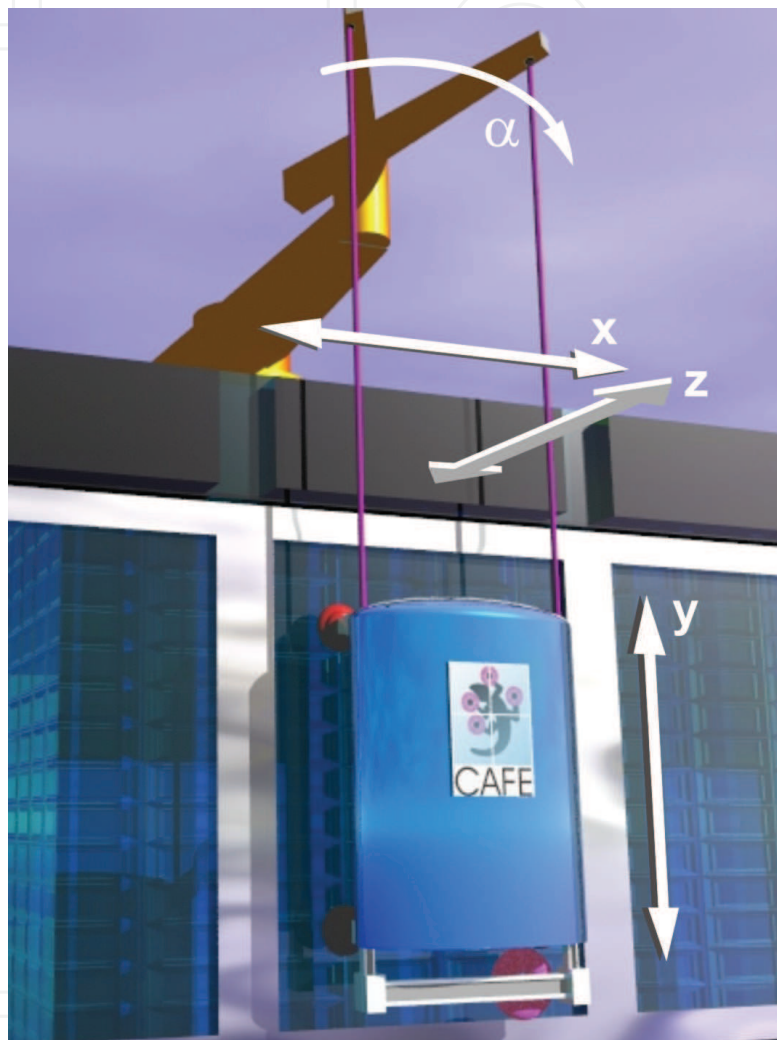


Fig. 3. *CAFE* Façade Cleaning System concept.

As we have mentioned, completely autonomous systems result too expensive for the market and for this reason the proposed system has been designed to perform the cleaning task in a semi-automatic way. This means that many of the tasks are performed in a completely autonomous way; however, because of security and economic considerations, a human operator permanently controls the robot operation.

A single person, physically situated on the ground below the robot, operates the complete semi-automatic cleaning system. However, most of the task can be performed in a completely automatic way. The operator has to install the machine at put it in work giving periodical attendance when necessary (filling deposits, changing task, etc.). To achieve this, it is necessary to program the robot adapting it to the building's façade. This task is

necessary only one time, previous to the work and it is not be very time consuming. Due to the low cost of the system, buildings with large façades can have dedicated machines.

The robot cleaning system has been decomposed in four different modules (Figure 4):

- Cleaning Module (CLM)
- Kinematics Module (KM)
- Carrier Module (CaM)
- Control Module

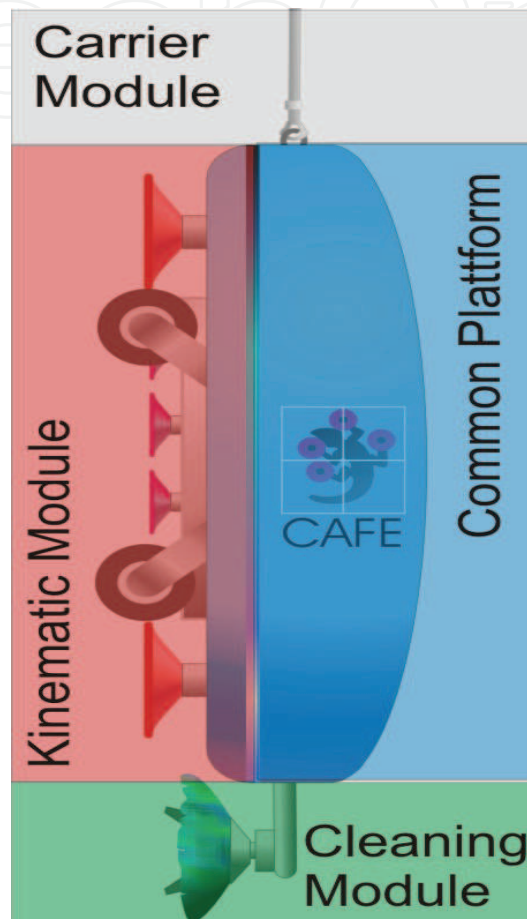


Fig. 4. Arrangement and interconnections of the CAFE hardware modules

The Cleaning Module is in charge of the actual façade cleaning. It mainly consists in a cleaning mechanism and a positioning system. The most important features of the cleaning module include:

- Cleaning with brushes and water (environmentally-friendly)
- Water recycling system (low water use)
- All actuators pneumatic (compliant motion, simple control structures, robust)
- Passive degrees of freedom in kinematics to account for unevenness in façade surface and to protect against hard collision with framework when moving up and down the façade (braking distance)
- Sensors for detecting glass framework and overseeing the condition of the cleaning module

The cleaning system is able to clean up to between 3-10mm away from a window pane. The cleaning Module is shown in Figure 7.

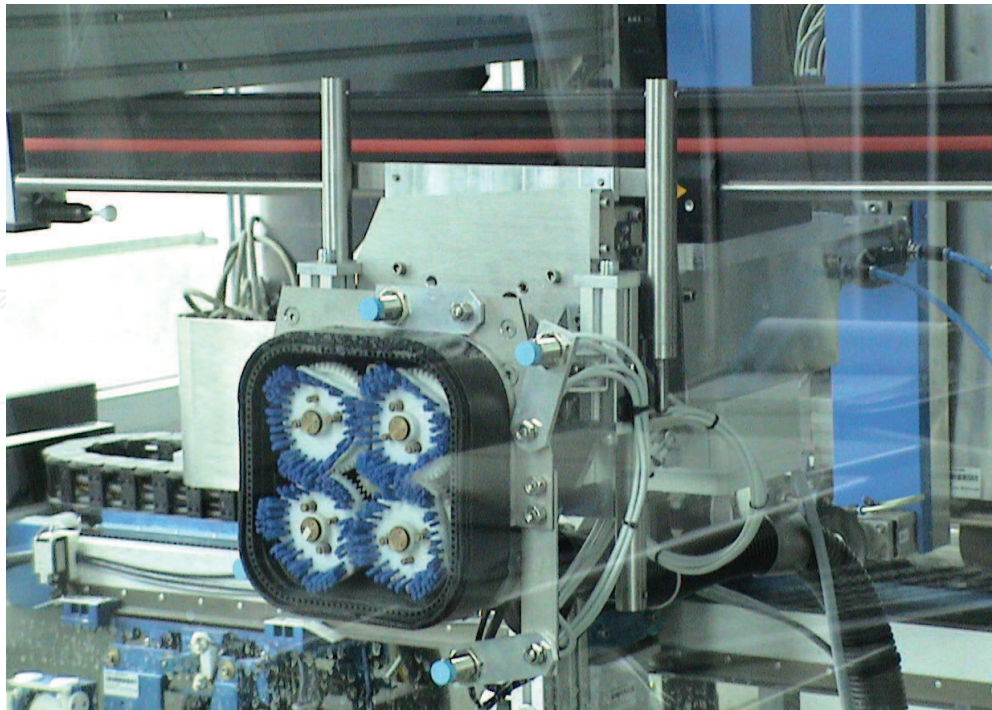


Fig. 5. CAFE Cleaning Module

The carrier is the part of the façade cleaning system that safely holds and provides horizontal, vertical and transversal motion to the kinematics and cleaning modules. It is installed on the building rooftop and moves over rails or on a concrete path (guided along the parapet), holding and providing motion to the cleaning and kinematics modules by means of cables. While the cleaning robot might be moved from one building to another, the carrier system will generally stay on the building rooftop.

The carrier must position the kinematics and cleaning modules on the façade at the beginning and between cleaning operations. The carrier positions the cleaning and kinematics modules in the x-axis through its movement along the rooftop. The winding or unwinding of the cables transmits the vertical motion and positioning in the y-axis. The adjustment of the distance to the wall z is obtained by controlling the α angle (see Figure 3).

The carrier must also be able to bring the kinematics and cleaning modules down to the floor or hoist and deposit them on the rooftop in order to perform maintenance operations, refill cleaning water or even lay those on a vehicle on ground to be transported somewhere else.

The Kinematics Module establishes contact between the cleaning head and the window pane. This contact is necessary for generating a reaction force of the cleaning head against the window pane. The system controller is in charge of control the presence or absence of the contact, accordingly to nominal and non-nominal situations.

In nominal situations the contact must be established during the entire cleaning task and hoisting operation. The break of contact can induce serious problems like bumps towards the facade caused by oscillations of the carrier. In case of this non-nominal situation a safety module must be activated in order to avoid oscillations.

3. CAFE robot control system

The term Control Module refers to the general architecture of the control systems of all the modules, and encompasses the concept for controlling each individual system. The cleaning

task has been decomposed into different actions that must be performed simultaneously by the different robot modules. The control module is in charge of the synchronization of all this tasks. The control scheme has been implemented using a hardware decentralized and software centralized control architecture. This architecture is considered more appropriate for the control system than a decentralized one (Figure 6).

3.1 Control architecture. Components distribution and communications scheme

The control system is distributed in three parts. The main controller (Control Module) is located in the Common Platform. The Carrier Module controller is located attached to the carrier on the top of the building. Finally, the operator, located on the ground, uses an interface device (PC or PDA). So, all the three parts include their own microprocessor-based computer. The main controller and the carrier controller are based on an embedded PC equipped with TwinCat-PLC core and Windows CE, allowing the combination of Windows based programming and PLC programming (IEC 61131-3) reliability. This configuration reduces the total cost of the system and simplifies the integration.

A wireless connection (Ethernet WIFI 802.11b) is used for the connection between the Control Module and the operator interface, and between the Control Module and the carrier. The safety of this communication is critical and it has been guaranteed by a watchdog system. In case of failure of the wireless communication, all the system adopts a safety position and can be recovered manually from the Carrier Module Control. The communication scheme is also shown in Figure 6.

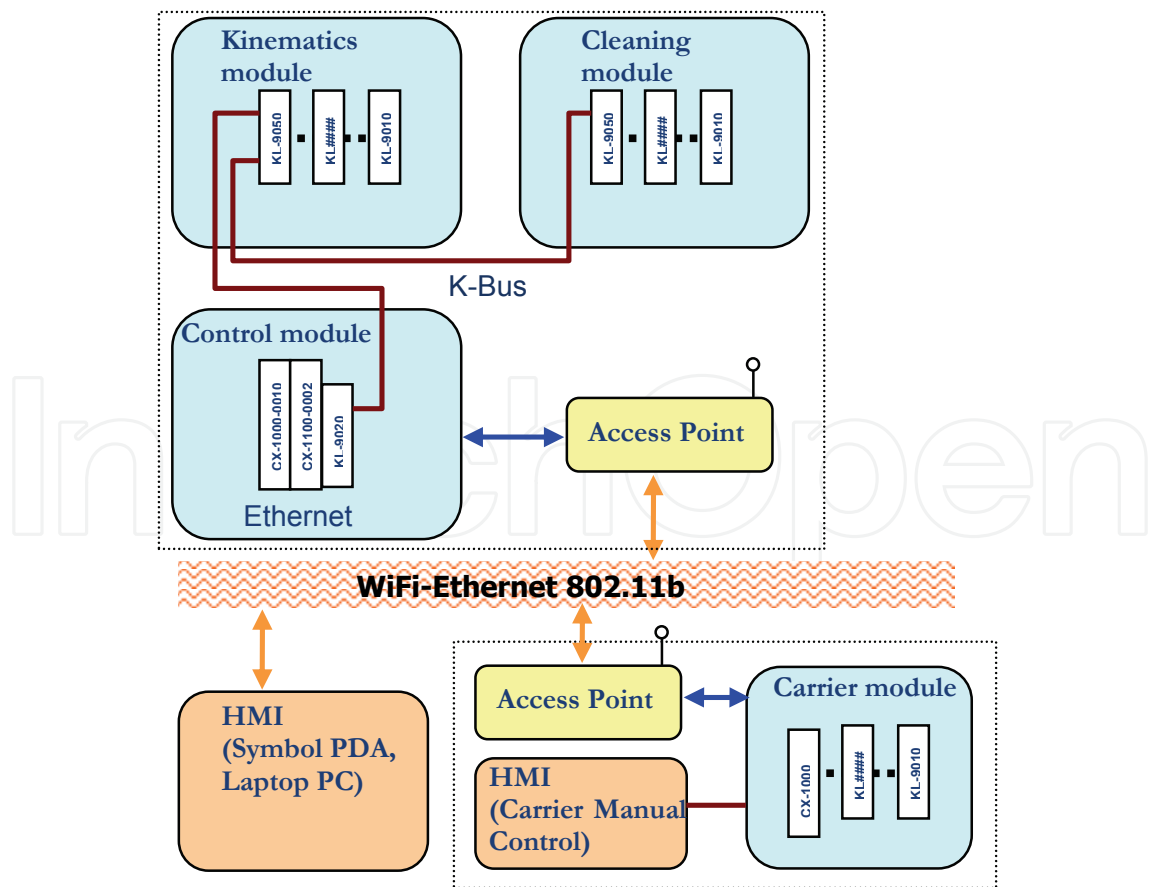


Fig. 6. Control System Architecture

The cleaning task has been decomposed into different actions that must be performed simultaneously by the different robot modules. The control module is in charge of the synchronization of all this tasks.

3.2 Software components

Although from the hardware point of view the robotic systems has three different microprocessor-based parts, there are five agents working in parallel, corresponding to the modules described in Figure 4 plus the operator interface:

- Control Module
- Kinematics Module
- Cleaning Module
- Carrier Module
- Operator Interface (HMI)

Additionally, each physical element requires a specific process in charge of establish the communications between the different elements. The communication virtual bus generation process is located in the main controller.

The distributed software architecture is shown in Figure 7.

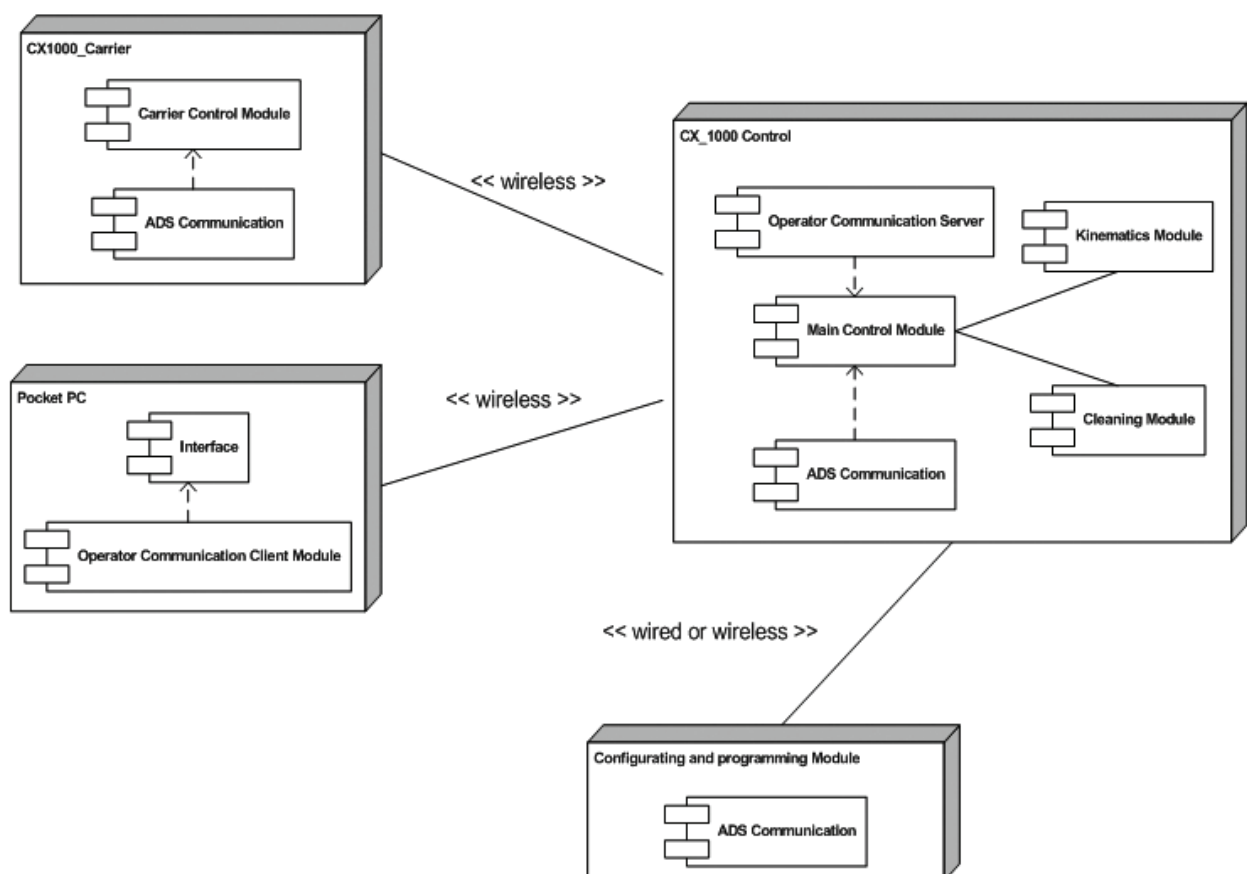


Fig. 7. Control System SW architecture and communications

All these elements are really constituted by different PLC programs executed in parallel and in an asynchronous way. To allow an adequate integration between them we have followed

a common methodology where the main controller demands services to all the other elements. There are specific processes for error managing, allowing error recovering.

The main mission of the Carrier Module is to control the absolute movement of the robot platform. This task must be accomplished synchronised with the Kinematics Module movements. Thanks to the mechanical design of the Kinematics Module, adaptive movements are allowed when the robot is fixed to the building façade. A low level control is performed in the Carrier Module. This low level control is in charge of the coordinated control of the carrier actuators, including de axis decoupling and the cancellation of the oscillations of the pendular robot movement.

The main controller, located in the Control Module, integrates the general state diagram of the complete system and synchronises all the elements. Additionally, it is in charge of the communications checking. At each cycle of the PLC program, the wireless connection is checked. If a lack in the communications is detected, an emergency process is started in both the Control Module and the Carrier Module. In the Control Module the emergency process commands the Kinematics and Cleaning Modules to adopt a safe configuration. In the same way of working, the controller of the carrier will stop any movement of the carrier and enables the manual control of the system.

For the operator interface a pocket-PC (windows CE) system was selected. This system allows intuitive and easy interface via wireless connection. The exchange of information between the Control Module and the Operator Module is based on a wireless WIFI-802.11b compliant connection. The communication can be encrypted under WEP protocol and the access point allows configuring specific IP directions to connect.

The Server-side is included in the Control Module whereas the Client-side is in the Operator Interface. Both the Client and the Server are programmed with C# and compiled for the Microsoft .NET platform (so .NET Compact Framework is required).

The communication is established after accepting the Server a request from the Client. No hand-shake protocol is implemented. The Server is able to detect both when the connection is fortuitously cut and when it has not been recently used and reinitiates its state to a new connection. The Client will receive the data and will only send Operator orders when produced.

3.3 Human-machine interface operation

There are two possible modes: manual and automatic. Additionally, there are three other modes: disconnection, emergency stop and error, that depend on the system status and where the normal cleaning operation is not possible.

In the automatic mode the cleaning task is performed with no need of further information after the system has been initialized. In the manual mode the operator must indicate the action to perform that can be accepted or not by the robotic systems depending on the command availability. The operator can select automatic or manual mode, but the mode does not effectively change until the main controller confirms it.

When the communication between the interface and the main controller is not properly established, the disconnection mode is set. In this mode the system is located in a safe position until the communication is re-established.

When the robot is not able to operate in the normal modes (manual or automatic) it is immediately set to the error mode and must be recovered manually.

The operator, using the interface, can activate the emergency stop and the robot is stopped in the next safe position. There are additional emergency buttons at the carrier.

The graphical user interface always shows the emergency stop option to the operator, as well as the battery status of the PDA device, the manual/automatic mode change and the WIFI connection status. In the automatic mode it shows the status of the current performed task, while in the manual mode allows the operator to select possible actions or to consult different variables using a simple colour code. Figure 8 shows different situations of the graphical user interface.

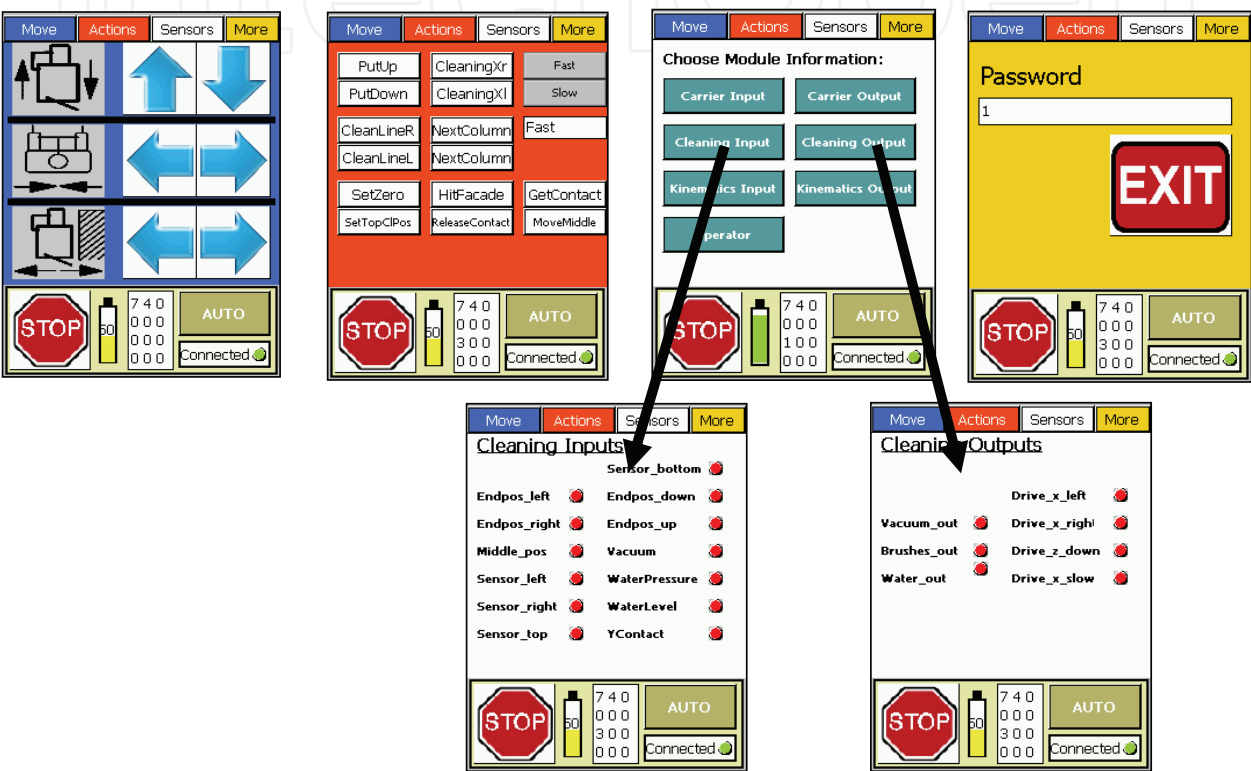


Fig. 8. Graphical User Interface

4. Results

After the development of the prototypes of the different modules, the complete cleaning system was merged. Some systems were refined and several parts of the control software were modified. The performance tests were successfully accomplished in automatic way. From the test operation the following was concluded:

- The overall cost of the system can be under 50 T€ on sale
- The operating costs are under 3 T€ per annum
- The cleaning speed in total is above 200 m2 per hour
- The system is usable at facade areas of under 7000 m2
- The cost saving is of up to 5 € / m2
- The roof car costs (depending from comfort) is around 20 T€ on sale
- The robotic system is able to serve more building of the owners
- The interface set cost for changeable operation on existing BMU s is under 15 T€

Figure 9 shows a real image of the CAFE prototype. After the project end a new company has been created by several partners to commercialize the machine.

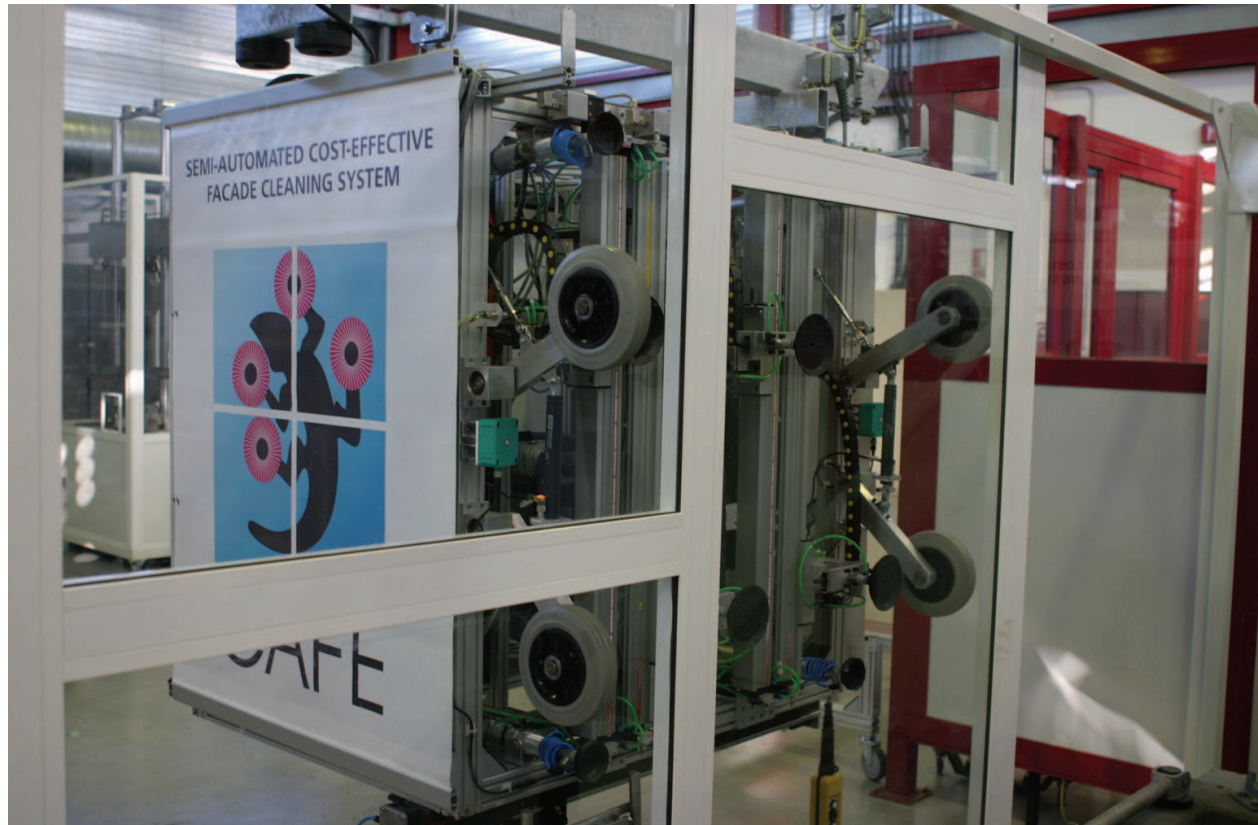


Fig. 9. CAFE Robotic façade cleaning system prototype

5. Acknowledgements

The authors wish to tanks the contribution of all the partners of the project and the support of the European Commission under the project CRAFT-1999-71236 CAFE.

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Robotics and Automation in Construction

Edited by Carlos Balaguer and Mohamed Abderrahim

ISBN 978-953-7619-13-8

Hard cover, 404 pages

Publisher InTech

Published online 01, October, 2008

Published in print edition October, 2008

This book addresses several issues related to the introduction of automaton and robotics in the construction industry in a collection of 23 chapters. The chapters are grouped in 3 main sections according to the theme or the type of technology they treat. Section I is dedicated to describe and analyse the main research challenges of Robotics and Automation in Construction (RAC). The second section consists of 12 chapters and is dedicated to the technologies and new developments employed to automate processes in the construction industry. Among these we have examples of ICT technologies used for purposes such as construction visualisation systems, added value management systems, construction materials and elements tracking using multiple IDs devices. This section also deals with Sensorial Systems and software used in the construction to improve the performances of machines such as cranes, and in improving Human-Machine Interfaces (MMI). Authors adopted Mixed and Augmented Reality in the MMI to ease the construction operations. Section III is dedicated to describe case studies of RAC and comprises 8 chapters. Among the eight chapters the section presents a robotic excavator and a semi-automated façade cleaning system. The section also presents work dedicated to enhancing the force of the workers in construction through the use of Robotic-powered exoskeletons and body joint-adapted assistive units, which allow the handling of greater loads.

How to reference

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Ernesto Gambao, Miguel Hernando and Dragoljub Surdilovic (2008). Development of a Semi-Automated Cost-Effective Facade Cleaning System, *Robotics and Automation in Construction*, Carlos Balaguer and Mohamed Abderrahim (Ed.), ISBN: 978-953-7619-13-8, InTech, Available from:

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